Collaborative Proposal to Extend ONR YIP research with BRC Efforts

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Award Number: N00014-10-1-0490

LONG-TERM GOALS

The long-term scientific goals of this research project are:

1. To develop an understanding of how some sources of error affect ocean predictability.
2. To gain experience and develop ideas for the limitations to the predictability of oceanic processes.

OBJECTIVES

The primary objectives of this project are: (i) to undertand the importance of model uncertainty; (ii) to assess the influence of uncertainty on predictability; and (iii) to collaborate and learn from fellow BRC projects.

APPROACH

To improve forecasts of the ocean circulation, we must deal with many scales of physical processes and how they are represented within numerical models. The ocean contains energy at many scales from planetary (megameters) down to small turbulent mixing (centimeters). The dominant range of energy exists in the mesoscale. Most of the efforts on assimilation and predictability are concerned with the mesoscale and even submesoscale. There are some regional seas where energy at other scales are of similar strength. Regions such as Hawaii, South China Sea, Philippine Sea, and others contain significant baroclinic internal wave energy generated by the conversion of the barotropic tides. The energy of these internal tides interacts with the mesoscale with higher energy modes dissipating quickly into the background flow leaving low mode baroclinic waves. The interaction between the mesoscale and internal waves is an active area of research in the ocean, and is not well understand how energies cascade between the two scales.

We continue to be the forefront of working to both represent and assimilate data in regions where baroclinic tidal flows are as great as the mesoscale, primarily Hawaii and the Philippine Sea, both of which are important strategic regions for the Navy. Around Hawaii, internal tides heave the thermocline over 100m as they propagate and greatly affecting *in situ* observations from platforms such as gliders, acoustic tomography, moorings, etc. For fixed observations with frequent enough observations, these signals are easily identified; however, in non-traditional observations, the internal wave signals typically cannot be extracted. For instance, as gliders pass through time and space, there is a smearing of the internal wave energy. Likewise, heaving of the density surfaces by internal waves changes the propagation of sound impacting tomographic measurements. The surface bounce of internal waves has a random phase due to density variations in the background stratification, which impacts high-frequency radar measurements adding significant uncertainty in the estimate of the surface flow.

In addition to the internal waves, accurate representation of the surface layer between the ocean and atmosphere has been found to be a significant issue for our studies due to strong diurnal variability in sea surface temperature, and rapid forcing by wind shifts in the upper waters that are captured by the HF radar. Because both of these datasets are assimilated in near real-time by our system, the model must represent the processes as well as possible, which requires a better surface layer representation.

The ocean model used in this research is the ONR-funded Regional Ocean Modeling System (ROMS): a free-surface, hydrostatic, primitive equation ocean model discretized with a terrain following vertical coordinate system. The model has multiple sub-gridscale parameterizations of vertical mixing along with many options for open boundary conditions. Time-splitting of barotropic and baroclinic motions enables efficient time integration. ROMS has been successfully used to model many regions of the world ocean (see `http://www.myroms.org/papers`) and is a widely used community resource.

WORK COMPLETED

During the current reporting period, we have published a manuscript (Janeković et al., 2013) that examines assimilation in a high-resolution coastal domain (near 50m resolution). In such regions, the normal assumptions (primarily an initial value problem) no longer hold; however, we were still able to use the linear assumption to assimilate the data with the adjoint method. The predictions remained strong primarily due to the strong tidal circulation. We found that only the wind stress and boundary conditions were capable of controlling the circulation over four days, and that the initial value problem did not contribute to improved predictability.

In addition, we performed an 18 month reanalysis of the Hawaiian region using several HF radio datasets provided by Prof. Pierre Flament of the Univ. of Hawaii. This reanalysis has allowed us to examine the dominant dynamics for controlling the vorticity balance in island regimes, which will play an important role for determining our predictive skill.

RESULTS

As part of the ongoing efforts of my Young Investigator Program award (ONR #N00014-09-1-0939) as well as the operational NOAA Integrated Ocean Observing System, we have built an operational, real-time assimilation and prediction system for the main Hawaiian islands. This system provides a foundation laboratory for research into state estimation and predictability. In support of these efforts, we have worked to better represent the highly variable representation of the interface between the ocean and atmosphere to improve our predictions and assimilation of sea surface temperature and HF radar data.

As shown in Figure 1, the correlation between the posterior field and the prediction changes dramatically only when considering either boundary or wind forcing control vectors. Initial conditions and surface heat fluxes played very little role in controlling the coastal circulation of Oahu. This is an important result for working with assimilation methods closer and closer to shore with higher resolution and finer dynamical scale. This has important impacts for our predictability because we must improve our prediction of the larger scale to improve the near-shore predictability.

Using the Hawaii model, we performed the reanalysis previously described and analyzed the vorticity balance. Using the model fields, we can find the vorticity balance as given by,

$$\frac{\partial \omega}{\partial t} = -\left(\mathbf{u}\frac{\partial \omega}{\partial x} + \mathbf{v}\frac{\partial \omega}{\partial y}\right) - (\omega + f)\left(\frac{\partial \mathbf{u}}{\partial x} + \frac{\partial \mathbf{v}}{\partial y}\right) + \left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}\right) + \left(\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y}\right), \quad (1)$$

where ω is the ocean surface relative vorticity. Each of these terms can be examined to understand their role in controlling the vorticity. As shown in Figure 2, the wind has a nearly instantaneous impact in the island channels; whereas, the advective term controls much of the vorticity balance away from the island on a longer (4 hour) time lag. There is little contribution from the divergence of vorticity, and the friction term (as found by examining the vorticity between the surface and underneath layer of the ocean) only impacts where the Ekman forcing is strong.

For predictability, this illustrates that for both sub- and mesoscale vorticity of our region, we must have both the wind field and the large-scale advection of vorticity correct for localized prediction.

IMPACT/APPLICATIONS

These results have altered the way in which our local and nearshore assimilation and prediction systems are built. The wind-stress has significant influence on the local vorticity generation; however, it is the larger-scale that advects vorticity and dominating flows into the near-shore regions for deep ocean island environments (that lack a wide, shallow continental shelf).

TRANSITIONS

We have published four papers with partial support from this project (with the remaining support from #N00014-09-1-0939). Another paper is in final preparation detailing the dynamics that control vorticity.

RELATED PROJECTS

This project is collaborating with the following ONR supported projects:

- "A community Terrain-Following Ocean Model (ROMS)", PI Hernan Arango, grant number N00014-08-1-0542.

REFERENCES/PUBLICATIONS

These papers and theses have been written under full or partial support of this program.

J. de Souza and B. S. Powell. The ocean surface vorticity balance in Hawaii from a regional reanalysis. *J. Geophys. Res.*, in final prep, 2013.

I. Janeković and B. S. Powell. Analysis of imposing tidal dynamics to nested numerical models. *Cont. Shelf. Res.*, 34:30–40, 2012.

I. Janeković, B. S. Powell, D. Matthews, M. A. McManus, and J. Sevadjian. 4D-Var Data Assimilation in a Nested, Coastal Ocean Model: A Hawaiian Case Study. *J. Geophys. Res.*, in press, 2013.

D. Matthews, B. S. Powell, and R. F. Milliff. Dominant Spatial Variability Scales from Observations around the Hawaiian Islands. *Deep-Sea Res., Part I*, 58:979–987, 2011.

B. S. Powell, I. Janeković, G. S. Carter, and M. A. Merrifield. Sensitivity of Internal Tide Generation in Hawaii. *Geophys. Res. Let.*, 39(L10606):1–6, 2012. doi: 10.1029/2012GL051724.

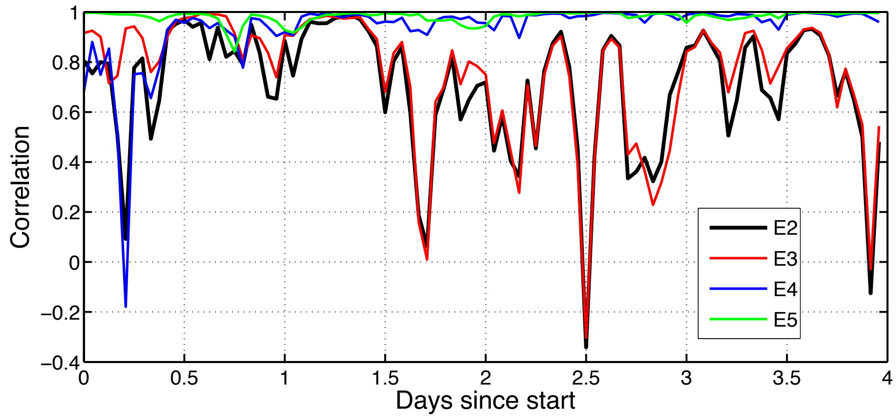

Figure 1: Correlation between various control vectors of the assimilation (initial conditions, boundary forcing, wind stress, and heat flux). For near coastal environments, we see that only when adjusting boundary conditions do solutions deviate from the prior prediction; hence, they are not initial value problems, as the initial field is swept away in less than 1.5 days.

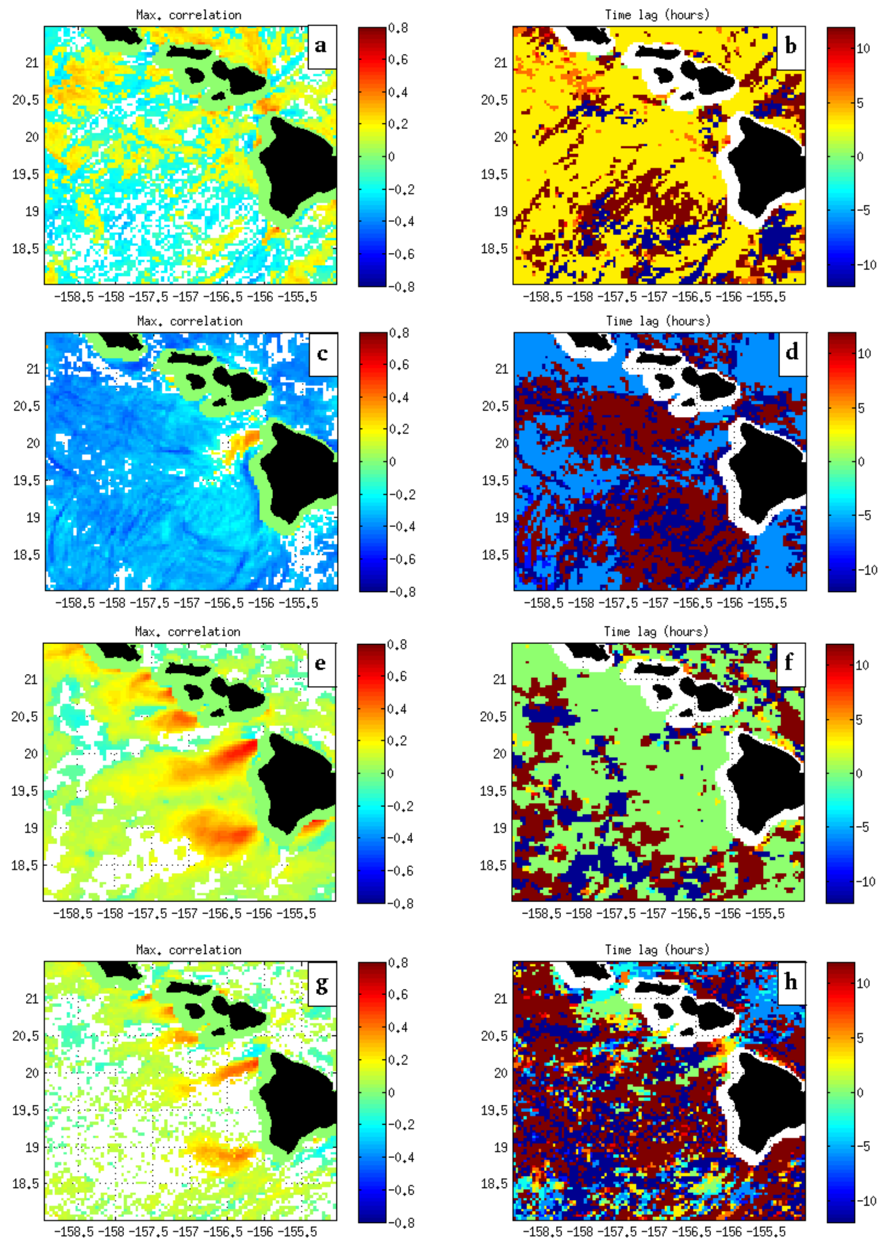

Figure 2: Maximum correlation (left) and corresponding time lag in hours (right) for: (a,b) the vorticity advection; (c,d) the vorticity divergence; (e,f) vorticity wind forcing; and (g,h) vorticity friction.